Tracking Land-Use/Land-Cover Change in a Watershed of the Cordillera Blanca

A Senior Honors Thesis

Presented in Partial Fulfillment of the Requirements for graduation *with research distinction in Geography* in the undergraduate colleges of The Ohio State University

by

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Introduction

Climate change is a global phenomenon that has different regional impacts. One region that stands to be acutely affected by climatic shifts is the Cordillera Blanca. The Cordillera Blanca is a mountain range in northwestern Peru that is home to the world's largest concentration of tropical glaciers (Mark et al., 2010). These glaciers have been severely affected by climate change, losing 11 to 30 percent of their area over the last four decades (Bury et al., 2008). As these glaciers melt, the hydrologic regime of the area changes rapidly, endangering the well-being of the people who depend upon the glaciers as a source of water. Much research has been undertaken to understand the precise nature of these glacial changes from a physical standpoint; however, less research has been conducted on the social aspects that may affect regional water resource stability (Mark, 2008). Studies have shown that the flow of the Rio Santa, the primary recipient of the glacial waters, has decreased over the last few decades (Mark et al., 2010) (Figure 1). One hypothesis is that land-use/land-cover change (LULCC) in the surrounding valley (known as the Callejon de Huaylas) has increased water withdrawal rates and impacted the river. In the interest of testing this hypothesis and adding important research on the social aspects of the regional system, an analysis of LULLC in the Callejon de Huaylas over roughly the last 20 years was carried out.

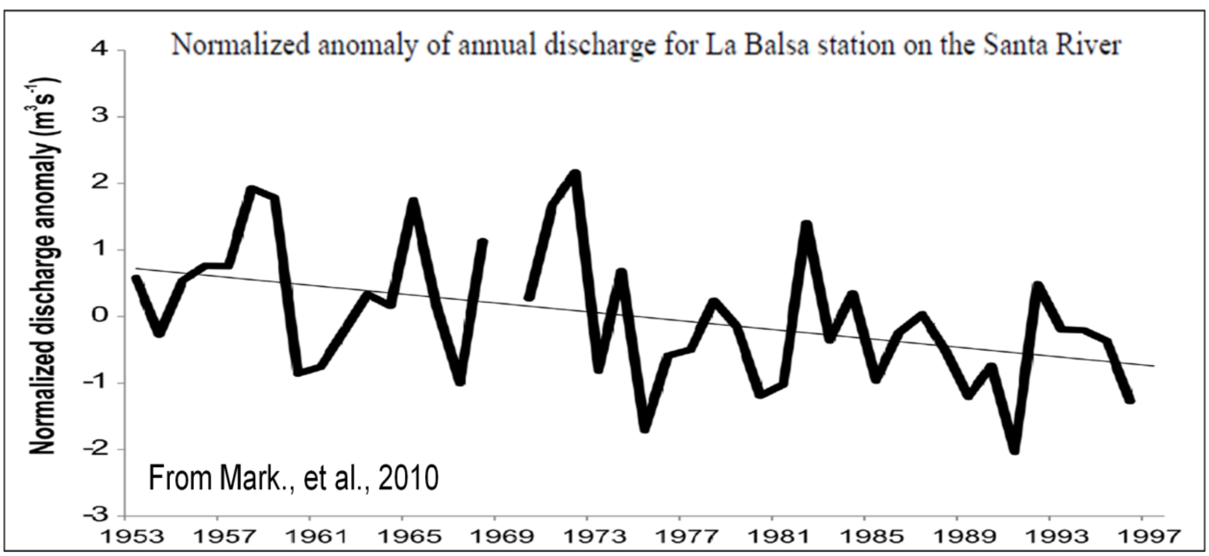


Figure 1. *The decrease in Rio Santa volume over the last 5 decades.*

Study Area

The study area comprises the watershed of the Rio Santa that lies within the shadow of the Cordillera Blanca and its melting glaciers. The Cordillera Blanca is renowned for its high degree of glaciation, but anthropogenic climate change has resulted in the diminishment or outright loss of many glaciers in the range (Bury et al., 2008). It is expected that many of the glaciers will vanish over the next few decades (Mark et al., 2010). This glacial loss will have serious implications for the well-being of the people living in the Callejon de Huaylas, the Rio Santa valley west of the Cordillera Blanca. Studies indicate that the Cordillera Blanca provides up to 40 percent of the Rio Santa's water year round, and up to 66 percent of the water during the dry season; much of this water is affected by glacial hydrology (Mark, 2008). The glaciers also act as hydrologic buffers, providing water during the dry season and impounding potentially flood inducing precipitation during the wet season (Mark & McKenzie, 2007). As the glaciers melt, the area will lose these buffered properties and become more prone to both drought and flood. In addition, there is research that indicates that the flow rate from the glaciers is increasing as they melt (Mark et al., 2010), a situation that has created the possibility of unsustainable land use practices arising from this temporary surplus of water (Mark, 2008). All of these changes are already having an impact on local residents. Studies show many feel that less water is available, especially during the dry season (Mark et al., 2010). This could be caused by the shorter wet seasons (Postigo, Young, & Crews, 2008) or the fact that streams may become unstable and ephemeral as the glaciers recede (Young & Lipton, 2006). The loss of water to the Rio Santa and the loss of the glaciers are clearly important to the health of the region, and the role of LULCC is not yet known to a satisfactory degree.

Compounding the glaciers' retreat, social changes have also affected the region. The beauty of the glaciers and unique geomorphology of the region lead to the establishment of Huascaran National Park in 1975 around almost the whole of the high Cordillera Blanca (Byers, 2000). The park, which was designated a UNESCO World Natural Heritage Site in 1985, has brought tourism and development to the region (Sevink, 2009), further affecting local water use. This is particularly pertinent given the demographic makeup of the Callejon de Huaylas. The valley's population is roughly a quarter million and growing (Mark, 2008). There is a general bifurcation between the wealthier Spanish peoples who populate the small cities clustered around the Rio Santa and the poorer Quechua farmers who inhabit the rural slopes of the valley. The farmers generally grow maize, barley, wheat and potatoes, as well as graze cattle, sheep and llama. However, there is evidence that many farmers are moving to the cities to escape the tough times on the slopes, causing urbanization (Young & Lipton, 2006). Increased urban areas could potentially exacerbate flooding (Hugo & Ordones, 2004) or increase water usage per-capita. Peruvian mining claims have also exploded in the wake of a series of neoliberal reforms (Bury, 2005). Local mines are heavy water users and their expansion attempts can affect local landholdings and land use (Bury, 2005).

Peru underwent a severe agrarian reform in 1969 which broke up large rural landholdings, collectivized agriculture, and forced farmers to nucleate into rural towns (Bury, 2005; Young & Lipton, 2006). When these reforms were reversed in the 80's and 90's as Peru privatized under a neoliberal regime, many of the farmers were bought-out by mining corporations (Bury, 2005). These new mines reduced the available land for traditional vertical transhumance, and eliminated informally managed land tenure agreements, both conditions that caused an intensification of agriculture as farmers have less land to use (Bury, 2005). These dynamics have a multitude of consequences for the study area, and it is plausible that the resulting LULCC has been a factor in the changing hydrologic regime.

Data

The data collected were a series of images taken of the Cordillera Blanca by Landsat 5's TM sensor. All images were downloaded from the USGS website with the help of their Global Visualization Viewer tool. The Landsat series of images were selected as they were the only data that covered the whole Rio Santa watershed in large scale images and had been in operation for the requisite amount of time; the relative novelty of satellite technology made locating images on a multidecadal time scale an issue for other satellite programs. Higher resolution images such as those taken by Quickbird or IKONOS lacked the spatial coverage and temporal longevity needed for this analysis. Older Landsat 3 MSS images lacked the requisite spatial resolution, while newer Landsat 7 images were compromised by a failure of the Scan Line Corrector beginning in 2003. Ultimately eight images (two per time period) from Landsat 5 were chosen, including images from May 12, 1986, September 1, 1986, May 3, 2006, and September 8, 2006. The fact that the study area was split North/South between images in each time period meant that two images for each date had to be obtained for full coverage. These particular dates were chosen because they showed relatively low cloud cover, a problem for many of the other potential images, and were take near the same time of year, to control for seasonal changes in land cover. Two time periods were selected from each year to help control for seasonal variation in land coverage; May and September were selected in particular because they show the study area at the beginning and end of the dry season, they were both relatively cloud-free, and they were some of the few months consistently available. The USGS images have also been preprocessed to a degree, eliminating the need for geometric correction.

Methodology

All processing was done using ERDAS IMAGINE software, with some images post-processed into maps using ESRI ArcGIS. Because the data were downloaded in separate bands, the bands were first stacked together into one file using Erdas IMAGINE to produce multiband images and allow for color display. Bands 1-5 and 7 were stacked and used in the analysis; the thermal band was excluded. Following stacking, the images from the respective dates were mosaicked together using IMAGINE's MosaicPro function. This process was necessary because the study area spans two images, but the procedure was simple and automated. The resulting mosaics for 1986 (Figure 2) and 2006 both showed relatively few artifacts from the processing, although the May 2006 image had a small gap of around 2-3 pixels between the two images. This was deemed to be of little statistical effect and was ignored.

Ancillary data of the portion of the Rio Santa watershed within range of the Cordillera Blanca were then obtained from files stored on the computers at Byrd Polar Research Center. The watershed shapefile had a slight data error and part of its southwestern portion had not been included when the file was created, but the absent area was relatively small and deemed insignificant. The watershed was then extracted from the larger images using the "mask" function in IMAGINE. This process worked well for 1986 (Figure 3) as well as 2006.

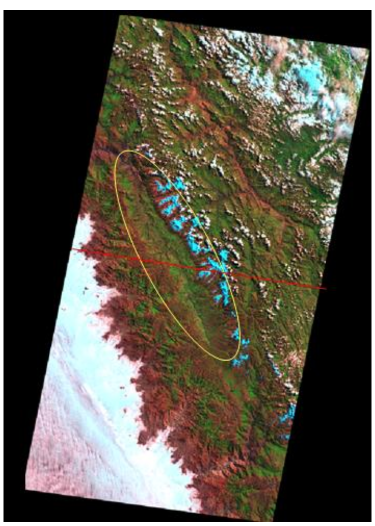


Figure 2. *An example of a mosaicked image. Full extent of May 12, 1986, shown in 7,4,2 false color. Approximate study area in yellow, mosaic line in red.*

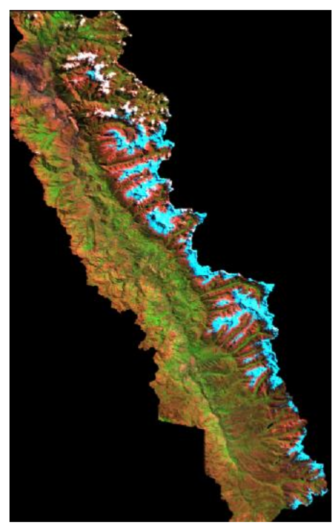


Figure 3. *An example of the study area. Extracted watershed for May 12, 1986, shown in 7, 4, 2 false color.*

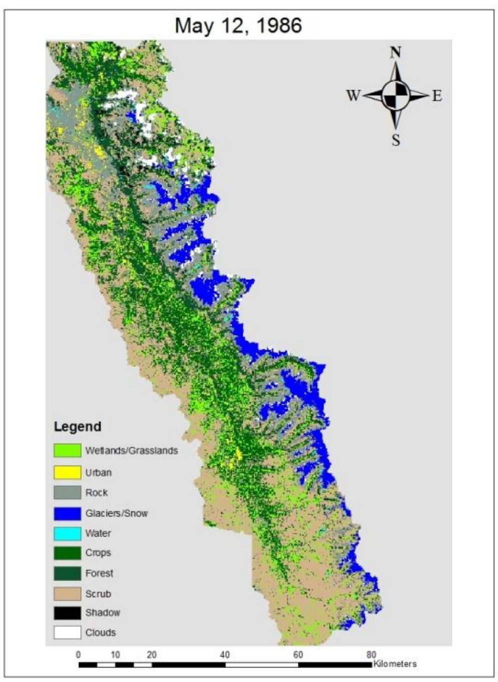
A simple supervised classification of the four images and comparison of the results was then performed. A comparison of the classified results is simpler than an overlay analysis, and does not typically require prior geometrical or atmospheric correction (Jensen, 2005). While the images were already preprocessed by USGS, it was not perfect with about a 1-2 pixel difference in the area captured by the mask; while not very large over a 6.6 million pixel study area, this difference would be enough to stymie an overlay analysis that requires near perfect registration. The large study area and low spatial resolution of the sensor made the geometric correction to fix this small difference very difficult. It was also impossible to obtain the reference data either first hand or online to make accurate atmospheric corrections. It was judged between the lack of geometric and atmospheric correction that overlay analysis would likely add more error than accuracy and that the data already had high enough quality for a comparison analysis.

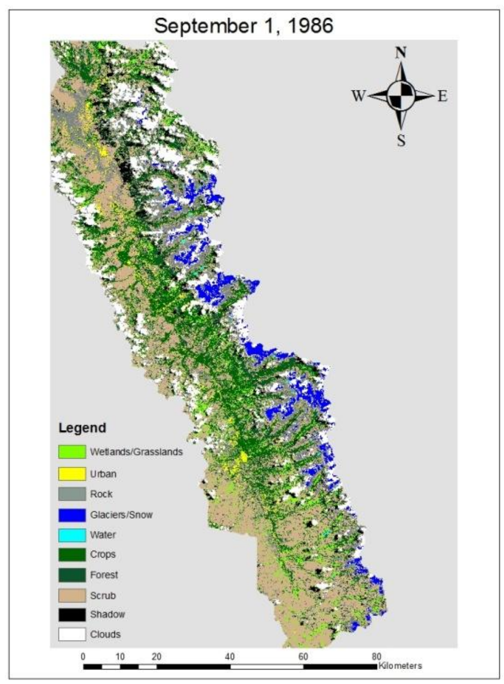
A good classification study must have epistemologically sound classes, and an attempt was made to adhere to this guideline. Ten classes were ultimately defined:

1. *Clouds*
2. *Shadows*
3. *Glacial/Snow*
4. *Bare Rock*
5. *Urban*
6. *Scrubland*
7. *Tree* and *Shrub Stands*
8. *Water*
9. *Pasture/Wetlands/Grassland*
10. *Crop Cover/Agriculture*.

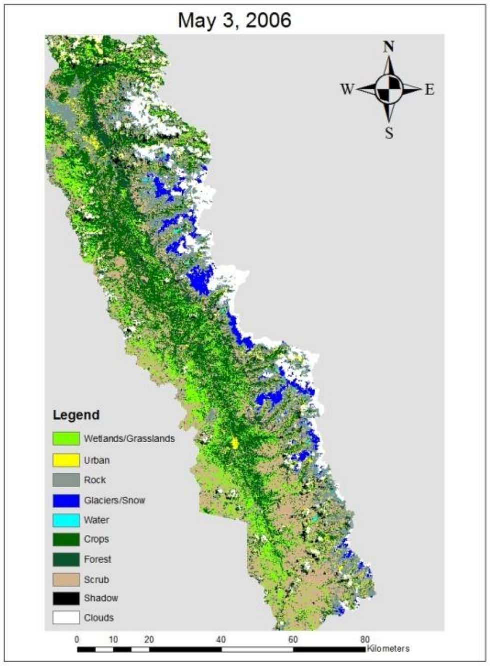
While several of the classes were fairly obvious and self explanatory, the differences in the vegetative classes were admittedly based on an ad hoc heuristic used for this project. The Callejon de Huaylas is a very old landscape that has been farmed for thousands of years, which makes it difficult to discern between a currently active agricultural areas and extinct fields. In addition, famers often rotate their crops annually and practice transhumance throughout the year. Thus, it was assumed that areas around the cities which displayed clearly delineated mosaic-patterned fields with areas of vigorous plant life were more likely to be active agriculture areas. More open vegetative areas were classified as pasture, grasslands, or wetlands, and more arid areas further up the hillsides were considered scrub. Although the spatial and spectral resolution of the sensor may not be high enough to pick out individual crops, this method at least gives a glimpse of potential agricultural change.

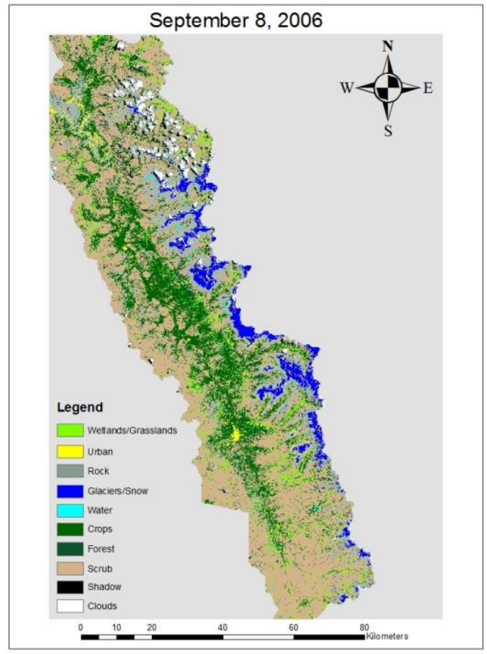
Supervised classification using the maximum likelihood algorithm was chosen as the method of classification. Generally, supervised classification methods are used when the interpreter is previously familiar with the area (Jensen, 2005). While the author did not have extensive a priori knowledge of the study area, close inspection of Google Maps (which included 1-2 meter spatial resolution visual imagery) assisted in identifying and referencing areas for use as training sites; unsupervised classification was seen as too difficult given the extreme topography and shadows of the region, which seemed to confuse the ISODATA algorithm. The Maximum Likelihood classification algorithm was chosen because it appeared to offer the most accurate results; the minimum distance algorithm gave less accurate classes and the parallelepiped classification algorithm produced unwanted, unclassified pixels. Training sites were chosen as best as could be determined following the guidelines set out in Jensen, with multiple training sites for each class being placed around the map, and each being of at least 60 pixels in size. The signatures from each training site in the class were combined and the classifications for 1986 (Figures 4 and 5) and 2006 (Figures 6 and 7) were then computed.





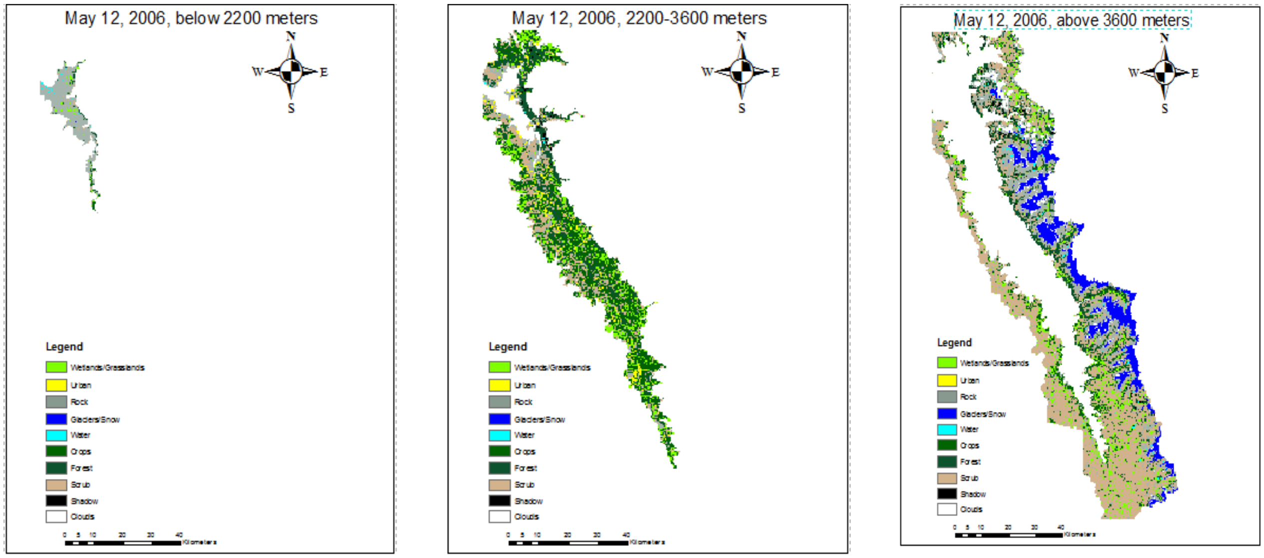
Figures 4 (left) and 5 (right). *Classified Images of the study area in 1986 before stratification.*





Figures 6 (left) and 7 (right). *Classified Images of the study area in 2006 before stratification*.

Preliminary attempts indicated that significant confusion occurred between the Urban and Bare Rock classes. Due to their similar spectral signatures (urban areas often use rock for building materials), many clearly rock areas had heavy occurrences of urban pixels. In addition, the Urban/Rock classes had the lowest rates of accuracy in the preliminary contingency tests. In order to fix this problem class stratification was performed. Stratification, the process of separating an image into parts to assist locally uneven signatures, has been found to be a useful tool for interpreting image data (Jensen, 2005). With the help of a Digital Elevation Model (DEM) of the region provided by Jeff Bury, the images were stratified into three areas: the area of the watershed below 2200 meters above sea level (Figure 8), the area between 2200 and 3600 meters (Figure 9), and the area above 3600 meters (Figure 10). The watershed's urban areas extend from Caraz at around 2300 meters to Recuay at approximately 3500 meters. A logical classification was then carried out where any urban pixels in the two areas outside the middle elevation range were thus classified as rock.



Figures 8 (left), 9 (middle) and 10 (right). *Examples of a stratified image at 2200 and 3600 meters.*

Results and Analysis

The results were as follows: In May 1986, Scrubland made up 33 percent of all land cover, Pasture/Wetlands were 10 percent, Urban was 1.2 percent, Bare Rock was 17 percent, Glacier/Snow cover was 7.7 percent, Water was 0.42 percent, Crop Cover was 14 percent, Tree stands were 14 percent, Clouds were 2.7 percent, and Shadows were 0.84 percent. In September 1986, Scrubland maintained to 33 percent, Pasture/Wetlands decreased to 4.6 percent, Urban increased to 1.5 percent, Bare Rock decreased to 16 percent, Glacier/Snow cover decreased to 4.4 percent, Water decreased to 0.17 percent, Crop Cover maintained to 14 percent, Tree Stands decreased to 9.3 percent, Clouds increased to 14 percent, and Shadows increased to 3.7 percent.

Twenty years later, in May of 2006, the results consisted of Scrubland at 24 percent, Pasture/Wetlands at 12 percent, Urban at 0.76 percent, Bare Rock at 17 percent, Glaciers/Snow cover at 3.4 percent, Water at 0.35 percent, Crop Cover at 23 percent, Tree stands at 8.2 percent, Clouds at 11 percent, and Shadows at 1.6 percent. By September 2006, Scrubland increased to 45 percent, Pasture/Wetlands decreased to 5.5 percent, Urban decreased to 0.58 percent, Bare Rock increased to 19 percent, Glacier/Snow increased to 4.4 percent, Water decreased to 0.3 percent, Crop Cover decreased to 18 percent, Tree stands decreased to 3.4 percent, Clouds decreased to 1.8 percent, and Shadows increased to 1.6 percent of total land cover (Figures 11 to 14).

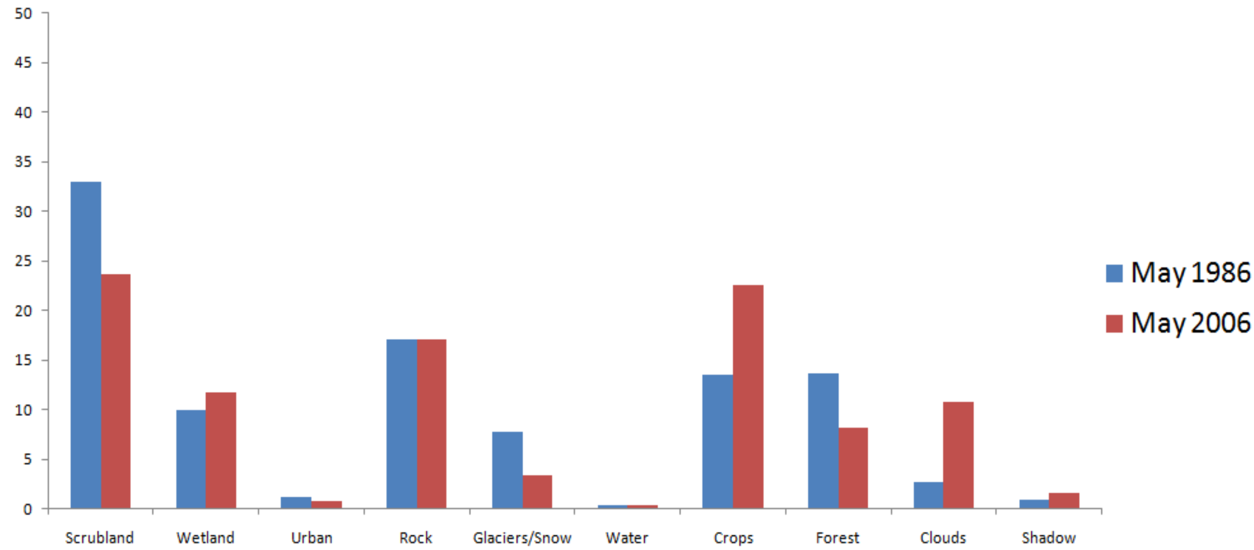


Figure 11. *Graph showing comparative percentage of total land cover for 1986/2006 May Classes.*

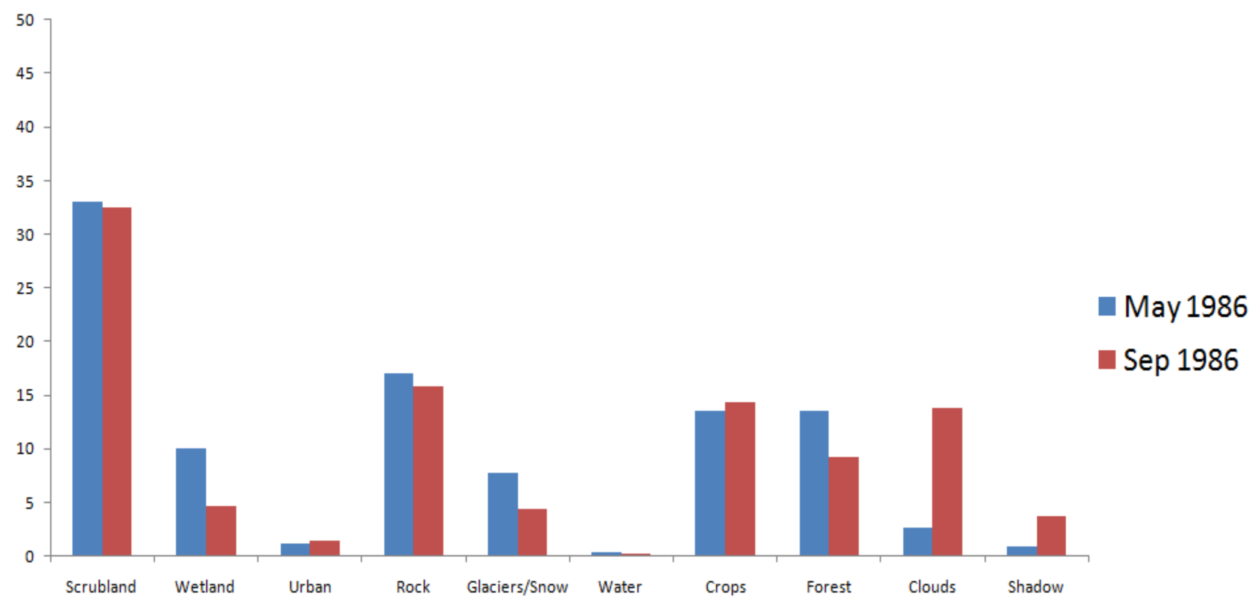


Figure 12. *Graph showing comparative percentage of total land cover for 1986 May/September Classes.*

Two months from each year were analyzed to help control for seasonal variations; the months of May and September lie on both sides of the Peruvian dry season. It is thus possible compare changes between 1986 and 2006 to account for climatic seasonality, both between years and intra-annually. It is apparent that forest covered suffered large decreases, losing 40 percent of its area from May 1986 to May 2006, and losing 63 percent of its area from one September to the next. In addition, there was less forest in each September than there was in May, perhaps the result of the dry season wilting vegetation and making it appear similar to other classes. A different picture emerges when examining pasture/wetlands, as there appears to be a slight increase from 1986 to 2006 in this grassland class. It too, however, appears to diminish equally over the dry season in both years, suggesting seasonal aridity. The final vegetative class, crops, increases by approximately 6 percent over the dry season in 1986, while in 2006 it decreases by 20 percent. As a whole, it is also more prevalent in the 2006 season, showing a growth of 9 percent of total land area in the May and 4 percent growth in September.

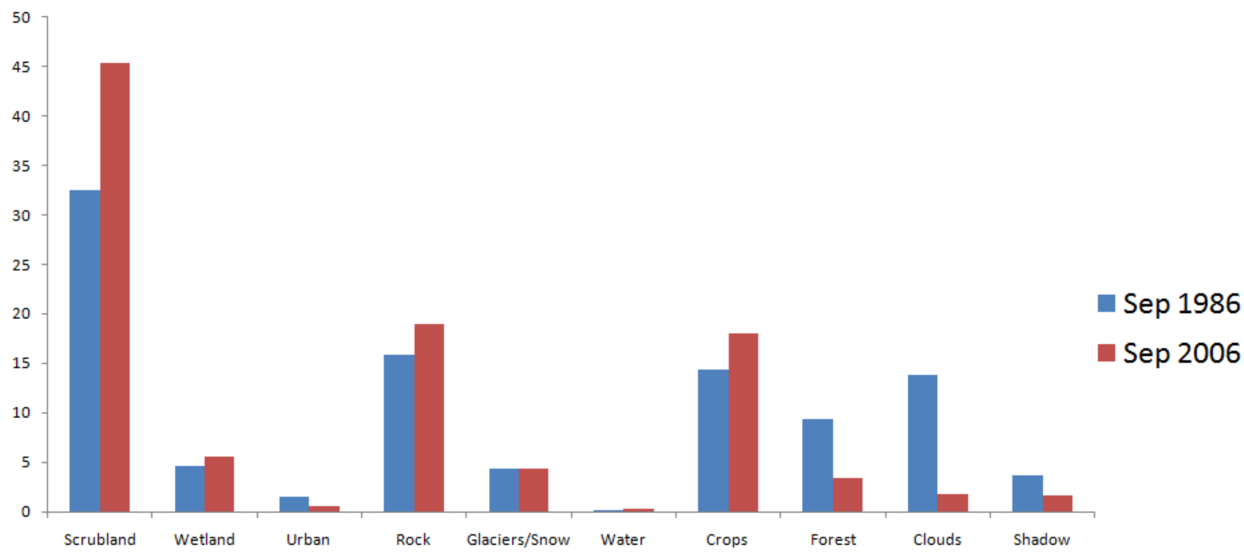


Figure 13. *Graph showing comparative percentage of total land cover for 1986/2006 September Classes.*

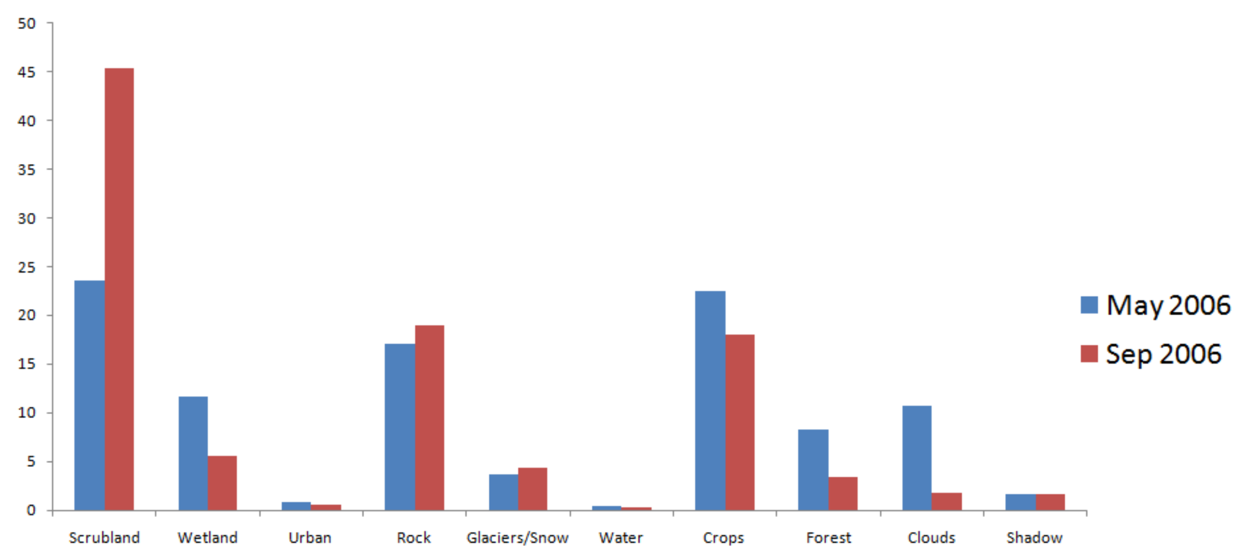


Figure 14. *Graph showing comparative percentage of total land cover for 2006 May/September Classes.*

The other classes, while less indicative of land use, still exhibited observable change. Scrubland held constant at 33 percent for 1986, but in 2006 made a rather dramatic increase from 24 percent to 45 percent of land cover. This large increase may be indicative of a much harsher dry season in 2006. Bare Rock maintained a presence of 15-20 percent per clip, although there was slightly more rock in 2006, perhaps a result of melting glaciers exposing bedrock or an expansion of shallow, silty mud flats along the Rio Santa . Snow and glacial coverage dropped by more than 50 percent from one May to the next, but remained steady at 4.4 percent for both Septembers.

Contingency tables (Tables 1 to 4) show the accuracy of classification schemes measured against their training sites; they are basically a measure of how well the algorithm classified the training areas given the training data it was provided. All classes in each of the four dates exhibited at least 80 percent accuracy. The highest degree of error was found for the crop class during the May months, possibly due to the prevalence of other vegetation types during those periods. The rock and urban classes also demonstrated some intermixing, although the classes were stratified to rectify those inconsistencies. While not equal to an empirical error matrix based on ground level observation, all contingency levels were around the range of 85-90 percent accuracy, considered appropriate for most remote sensing studies (Bolch, Menounos, & Wheate, 2010).

Table 1. *Contingency table for May 1986.*

Classified Data	Wetlands/G	Water	Crops	Glaciers/S
Wetlands/G	87.66	0.00	7.23	0.00
Water	0.00	94.06	0.00	0.27
Crops	9.77	0.00	81.80	0.00
Glaciers/S	0.00	0.51	0.00	99.20
Forest	0.46	0.25	4.15	0.00
Urban	0.49	0.13	2.23	0.00
Rocks	0.70	0.00	1.13	0.18
Clouds	0.00	0.00	0.00	0.35
Shadow	0.00	5.06	0.00	0.00
Scrub	0.91	0.00	3.46	0.00
Column Total	2844	791	6269	4905

Reference Data

Classified Data	Forest	Urban	Rocks	Clouds
Wetlands/G	1.39	0.16	0.00	0.00
Water	0.00	0.00	0.00	0.00
Crops	5.00	3.32	0.60	0.00
Glaciers/S	0.00	0.00	0.00	0.00
Forest	87.92	0.00	0.55	0.00
Urban	0.06	88.17	4.28	0.00
Rocks	0.37	8.19	92.81	0.13
Clouds	0.00	0.00	0.00	99.87
Shadow	0.96	0.00	0.00	0.00
Scrub	4.29	0.16	1.76	0.00
Column Total	3238	1868	1822	4497

Reference Data

Classified Data	Shadow	Scrub	Row Total
Wetlands/G	0.00	3.29	3349
Water	0.00	0.00	757
Crops	0.00	1.67	5821
Glaciers/S	0.00	0.00	4870
Forest	1.02	6.50	3842
Urban	0.00	0.42	1927
Rocks	0.00	2.46	2228
Clouds	0.00	0.00	4508
Shadow	98.98	0.00	849
Scrub	0.00	85.67	9668
Column Total	786	10799	37819

Table 2. *Contingency table for September 1986.*

Classified Data	Glaciers/S	Water	Shadow	Crops	Wetlands/G	Rock	Urban	Scrub	Forest	Row Total
	Reference Data									
Glaciers/S	100.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2151
Water	0.00	92.22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1470
Shadow	0.00	7.78	99.88	0.00	0.00	0.00	0.00	0.00	0.00	960
Crops	0.00	0.00	0.00	95.04	2.20	0.00	1.42	0.35	2.96	952
Wetlands/G	0.00	0.00	0.00	1.10	96.10	0.00	0.00	0.08	0.17	409
Rock	0.00	0.00	0.00	0.00	0.00	86.01	5.25	1.58	0.00	1328
Urban	0.00	0.00	0.00	1.10	0.00	8.98	92.13	8.20	0.00	1579
Scrub	0.00	0.00	0.12	0.33	0.00	5.02	1.20	89.30	0.63	2421
Forest	0.00	0.00	0.00	2.42	1.71	0.00	0.00	0.50	96.24	1731
Column Total	2151	1594	837	908	410	1415	1334	2597	1755	13001

Table 3. *Contingency table for May 2006.*

Classified Data	Shadow	Water	Urban	Rocks	Crops	Wetlands/G	Forest	Clouds	Scrub	Row Total
	Reference Data									
Shadow	99.27	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	676
Water	0.44	99.94	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1724
Urban	0.00	0.00	96.36	10.79	1.96	0.00	0.00	1.35	0.00	1142
Rocks	0.00	0.06	2.81	88.41	0.17	0.00	0.00	0.62	0.11	1164
Crops	0.00	0.00	0.62	0.32	85.88	8.06	1.71	0.00	1.51	2097
Wetlands/G	0.00	0.00	0.00	0.00	5.97	91.58	0.00	0.00	0.15	394
Forest	0.29	0.00	0.00	0.00	4.35	0.00	98.14	0.00	0.94	761
Clouds	0.00	0.00	0.21	0.16	0.00	0.00	0.00	98.03	0.00	2394
Glaciers/S	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
Scrub	0.00	0.00	0.00	0.32	1.66	0.37	0.16	0.00	97.29	2629
Column Total	681	1722	962	1260	2345	273	644	2438	2656	12981

Table 4. *Contingency table for September 2006.*

Classified Data	Shadow	Water	Glaciers/S	Rocks
Shadow	97.88	0.00	0.00	0.00
Water	2.12	99.67	0.00	0.00
Glaciers/S	0.00	0.00	99.93	0.00
Rocks	0.00	0.33	0.07	93.59
Urban	0.00	0.00	0.00	5.53
Crops	0.00	0.00	0.00	0.68
Forest	0.00	0.00	0.00	0.00
Scrub	0.00	0.00	0.00	0.19
Wetlands/G	0.00	0.00	0.00	0.00
Column Total	614	1230	1421	1030

Reference Data

Classified Data	Urban	Crops	Forest	Scrub
Shadow	0.00	0.00	0.00	0.00
Water	0.00	0.00	0.00	0.00
Glaciers/S	0.00	0.00	0.00	0.00
Rocks	3.80	0.28	0.00	0.41
Urban	94.59	1.96	0.00	0.72
Crops	1.50	94.74	1.55	1.16
Forest	0.00	1.47	98.45	0.14
Scrub	0.12	0.70	0.00	97.57
Wetlands/G	0.00	0.84	0.00	0.00
Column Total	868	1426	905	2921

Reference Data

Classified Data	Wetlands/G	Row Total
Shadow	0.00	601
Water	0.00	1239
Glaciers/S	0.00	1420
Rocks	0.00	1018
Urban	0.00	927
Crops	1.18	1424
Forest	0.24	917
Scrub	0.00	2863
Wetlands/G	98.58	430
Column Total	424	10839

Discussion

In addition to Land Use conversion, the observed changes may be related to environmental and methodological conditions. The increase in both the crop and grassland classes may be the result of milder weather in 2006, short term variability to which the forests would not respond as quickly. The differing results over the wet season could also be indicative of a non-linear relationship between seasonal variation and changes in the different plant classes. The fact that the glaciers actually seemed to gain area during the 2006 dry season, and that they remained unchanged in area over 20 years, can be explained from complications with cloud coverage, which often formed over the high altitude glacial areas. These clouds, while varying in severity from one image to the next, often obscured large areas of ice and snow, obfuscating readings. Urban and water changes also showed inconsistent readings, with water dropping from one May to the next but increasing from the compared September images; urban, likewise, displayed a concerted decrease during the twenty year interval. Visual identification and demographic data both suggest the urban area is in fact expanding, and the results for the urban and shadow classes are most likely the result of their classifications being affected by their small areas.

Relatively small areas would be more vulnerable to slight changes in the classification procedure, with just a few pixels drastically changing their displayed rate of change.

There are several caveats that must be considered when interpreting changes in these land cover data. One problem is that the annual variations in the weather could affect plant growth, so that the expansion and contraction of the vegetation classes could be affected by annual variations in precipitation and temperature. Overall climate change could also be a factor, as a generally warming climate could affect plant productivity and thus land cover. Another issue that is particularly hard to assess is the phenology of plants. Different plants will grow at different times of the year, and these annual changes can bias results. The data were taken from two months per year to help control for this variability, but the temporal resolution may not be high enough to fully account for yearly patterns; gathering data from all seasons is the best method for controlling this issue. Unfortunately, lack of data and cloud cover compromised efforts to obtain more frequent monthly records for the study years. Poor class choices also impeded the analysis, as there may be too many classes to positively separate themselves from one another; the above classes were chosen to be exhaustive and mutually exclusive, but many pixels may contain more than one type of land cover. In these cases "fuzzy" classification is often conducted to give probabilities of class types per pixel, but this was not attempted because it may further add error to an analysis partly based on ad hoc classes. Finally, the changes in cloud coverage from the 1986 data to the 2006 data biased the results, as each different date had slightly different cloud coverage. It was impossible to obtain completely cloud-free dates, but the clouds seemed to mostly cover the glacial areas and the rocky areas in the northern part of the study area. The cloud coverage may have thus affected the results from the rock and cloud classes, particularly the peculiar rise in snow coverage over 2006.

Methodological decisions were also made that lead to uncertainty in the results. Band 6, the longest wavelength thermal band of Landsat, was not included in the analysis due to its relatively low (120 meters) spatial resolution. There is a possibility that this band may have aided in interpretation, although similar studies have also eschewed its use (Silverio & Jaquet, 2009). Supervised classification was chosen over unsupervised due to ease of use and familiarity with the area, although the author's a priori knowledge of the study area was not extensive, and it is possible that the discontinuous satellite imagery of Google Maps did not provide a thorough enough reference for such an analysis. The topography of the region also presented problems of granularity, in that over varying gradients the pixels may cover unequal areas of ground. DEMs are often used to rectify this problem, but are required to have a spatial resolution at least four times greater than the base image (Silverio & Jaquet, 2009). A DEM of such resolution was unavailable and this adjustment was not attempted. In addition, the use of comparison instead of overlay analysis prevents disaggregation of the LULCC. With the comparison method it is impossible to ascertain shifts from one individual class to the next, and only general changes in land cover may be appraised. The landscape pattern of such changes represents important information that may be crucial to understanding the local land use changes, but cannot be gleaned from this analysis. Overlay analysis may have been possible with the data used, but was not attempted. The seasonal and interannual shifts in LULC classes are also very large, and most likely are the result of artifacts of the analysis process rather than accurate representations of reality.

With those caveats in mind, certain implications can be drawn from the results of the study. The apparent loss of the forests is a cause for concern. The forests are predominately imported Eucalyptus and Pine in the lower elevations and *Polylepis* in the upper elevations. *Polylepis* forests have been shown to act as hydrological regulators that provide water during the dry season (Jameson, & Ramsay, 2007). The leaves of the trees gather occult precipitation and the mossy underbellies of the forests regulate water flows into tributaries. The trees also serve as valuable sources of firewood to the local populace (Jameson, & Ramsay, 2007).There is some debate among ecological historians about the role of humans in the historical distribution of *Polylepis* forests, but current research indicates that many farmers feel that the quality of the forest is degrading (Jameson, & Ramsay, 2007). However, studies have also shown that, in one Peruvian valley at least, there appears to be little long-term destruction of forest quantity, although the density and health of the forests are declining (Jameson, & Ramsay, 2007). The study also reported that the forests appeared to cover roughly seven percent of land above 3800 meters, consistent with this study's findings. It is possible the loss of trees is a result of the loss of density in the forests, which may make them appear more similar to other classes. Regardless of the actual extent of forest loss, it is apparent that current trends in *Polylepis* forests may exacerbate future hydrologic issues and should be the subject of closer scrutiny.

The highland areas of rock are most likely exposed from past glacial retreat, while rock near the valley bottom is due to steep, arid, erosion-prone slopes and shallow floodplains of rivers (Silverio, & Jaquet, 2009). With continued glacier recession, one would expect to see an increase in highland rock outcrops. The rock class's relative stability may therefore be the result of changes in lowland silt offsetting changes in highland rock exposure.

The wetlands (locally called bofedales) and grasslands (known as puna) are important to local livelihoods. They serve as valuable pasture areas for herds of llamas, sheep, and alpacas (Postigo, Young, & Crews, 2008). Increased runoff from melting glaciers may saturate the ground and lead to the expansion of this class of land cover (Postigo, Young, & Crews, 2008), a result supported by this study. However, the increasingly arid summers may have escalating deleterious effects on the grasslands, as shown by the drop in area after the dry season. This is notable, as species such as the alpaca prefer wetter grasslands, and irrigation efforts have been undertaken to expand such land for grazing (Postigo, Young, & Crews, 2008). Increasingly unpredictable water supplies potentially threaten grazing operations on the slopes.

Glacial change is the most well known dynamic process in the region. The glaciers of the Cordillera Blanca compose approximately 26 percent of the world's total area for tropical glaciers, and studies have shown a significant decrease in area over the last few decades (Silverio, & Jaquet, 2005). The results for this study were unfortunately compromised by cloud coverage, but decreases from May 1986 to May 2006 of over 56 percent can be measured; this large number is most likely due to the cloud issues and the fact that snow was indistinguishable from glacial areas due to spectral similarities. Indices to control for such problems such as NDSI were made unusable due to the lack of atmospheric correction. The melting glaciers are likely to have a significant impact on the future livelihoods of the region. A loss of glaciers means unpredictable supplies of water, changing river courses, potentials for more droughts and flooding (Mark et al., 2010).

One potentially hazardous effect of the glacial retreat is the formation of proglacial lakes. While the reliability of the quantification of water in this study area may have been affected by its small areal extent, there appeared to be a slight increase from September 1986 to September 2006 (it declined from one May to the next). Nearly 100 percent of this water was found in high altitude alpine lakes. These proglacial lakes form as glaciers melt, with the flowing water becoming impounded against terminal moraines from previous glacial advances and retreats (Hubbard et al., 2005). These lakes are extremely unstable, as earthquakes and heavy precipitation can lead to overtopping of the moraines, which may lead to dam breaks and catastrophic flooding; over 32,000 people have fallen victim to proglacial lake flooding in Peru over the last 100 years (Hubbard et al., 2005). This danger is exacerbated by the general absence of government preparedness and reticence of the local authorities to act on this potential danger due to a perceived lack of personal advancement associated with proglacial flood planning (Hegglin & Huggel, 2008). The physical vulnerability of local peoples to lake flooding is compounded by social vulnerability to recover. As climate change increases the physical danger by filling the lakes, the social vulnerability wrought by adaption to those same climate shifts could significantly multiply the danger faced by locals.

The steadily decreasing urban area is most likely an artifact of this study's methodology. The urban area, despite efforts to control interference through stratification, is too small to track reliably. Despite the steadily shrinking urban area detected in this study, the cities of the Callejon de Huaylas are expanding both spatially and demographically (Mark et al., 2010). Tough economic times, exacerbated by diminishing land holdings, have caused many rural farmers to migrate to the cities (Bury, 2005). These expanding cities also spread impervious land coverage which can aggravate flooding, especially in the more poorly built areas of the cities (Hugo & Ordones, 2004).

The expansion of the cropped areas from around 14 percent in 1986 to around 20 percent in 2006 may be related to the social changes occurring on the slopes. While the wetlands and grazing areas have slightly expanded, mining companies have bought high altitude lands, shortening many farmers vertical transhumance, and forcing more intensive agriculture at lower elevations (Bury, 2005). The greater integration into a market economy may also be spurring an expansion of agricultural growth as many farmers transition from a subsistence to an export paradigm (Postigo, Young, & Crews, 2008).

Conclusions and Recommendations for Future Research

Ultimately, the goal of this study was to help quantify the effects of LULCC on the region's hydrologic systems. These results were inconclusive and potentially very inaccurate. Several classes seem to have pertinent effects on water resources of the region, but the accuracy and extent of their dynamism is difficult to ascertain. The expanding croplands may be indicative of more intensive agriculture, and thus more intensive water use. The expanding wetlands and pastures may be the result of increasing glacial melt waters, and thus indicate a potential sink for such water, as it saturates the water table. The same can be said for the lakes of the water class, as they act as a (perhaps temporary) reservoir for glacial waters. The fluctuating arid class may signify the increasing seasonality of available water. The urban areas, while not represented accurately in this study, are expanding and increasing their own water use. These all point to plausible scenarios for relating LULCC to the regions hydrologic resources, but further studies need to be done to establish the accuracy of such classification and quantify their contributions to the local water use model.

Problems with phenological cycles, cloud coverage, climate and weather variations, and intrinsic error of the classification algorithm must be accounted for; going forward, these problems will have to be corrected and new methods of analysis will need to be applied to improve future research. Overlay analysis, as opposed to comparison analysis, should be carried out. Multiple dates were used to help adjust for seasonal and phenological variations, but future studies should use higher temporal resolution. The collection of radiometric data and reference points would also allow for accurate atmospheric and geometric correction, allowing the use of spectral indices to aid interpretation and change detection to positively identify phenologically sensitive crops. Given the changes currently happening in the valley, this type of analysis would be an important step to help quantify important LULCC. If future research can accurately quantify the trajectory of changes to the urban and agricultural realms of the valley, both planners and scientists will have another powerful tool in their arsenal to help the residents of the Callejon de Huaylas adapt to their uncertain future.

The glaciers of the Cordillera Blanca are melting at an alarming rate, putting the well-being and prosperity of the local people in jeopardy. LULCC in the Rio Santa watershed is an important social research topic that can complement the physical research on hydrologic dynamics currently being done in the region. An examination of LULLC cover change from 1986 to 2006 showed that dense stands of trees declined, active cropping areas grew, pasturelands increased slightly. These results are useful as a start, but must also be integrated with knowledge of the social systems of the region to adequately plan for the future. This is especially important given that the climate of the Callejon de Huaylas is likely to be very different by the end of the 21st century due to climate change, and would necessitate adaptation (Urrutia & Vuille, 2009).

Climate change may seriously alter many of the accepted paradigms of human existence. The Cordillera Blanca, in particular, faces a crisis as a major component of its hydrological system disappears. This change, among others, may force the residents of the Callejon de Huaylas to radically alter lifestyles and traditions that span decades and even centuries. Knowledge of how these systems are changing is vital to help plan for a precarious future. LULCC analysis can hopefully provide one more brick in the foundation of a model on which to base sound decision making and actions.

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